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THE MARTIAN ENVIRONMENT

by ROBERT B. OWEN
Aero-Astrodynamics Laboratory

NASA

George C. Marshall Space Flight Center, Huntsville, Alabama

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ABSTRACT

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An intensive literature survey has been made of the present consensus on the surface and atmospheric conditions of Mars. Knowledge of the gross features of the Martian surface appears to be fairly complete, but there is sharp disagreement on the atmospheric conditions. While estimates of the surface temperature are in fairly close agreement and estimates of the surface pressure range from 10 to 150 millibars, other phenomena such as the blue haze are inexplicable. Formal design criteria for entry vehicles cannot yet be finalized because of the wide range of the environmental parameter values.

AUTHOR

NASA - GEORGE C. MARSHALL SPACE FLIGHT CENTER

NASA - GEORGE C. MARSHALL SPACE FLIGHT CENTER

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Robert B. Owen

SPACE ENVIRONMENT GROUP
AERO-ASTROPHYSICS OFFICE
AERO-ASTRODYNAMICS LABORATORY

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SUMMARY

Information on the environment of Mars has been gathered by use of a comprehensive literature survey. The landscape of the light and dark areas, the caps, and the canals has been formulated. Details of the atmosphere have been investigated, including such phenomena as the mysterious "blue haze." Estimates of such atmospheric parameters as constituents, pressure, and temperature have also been made.

Much interest has been aroused by the relatively low surface pressure values which have recently been derived. This is largely due to the direct effect such pressures would have on future vehicle design criteria. An evaluation of the spectroscopic measurements of Kaplan, Münch, and Spinrad, a major basis of the low pressure estimates, has thus been included as Appendix B. For equally important reasons, an evaluation of pressure estimates from polarimetric observations, widely used as a basis for relatively high pressure estimates, has been included in Appendix D. Pressure values range from 10 to 150 mb, and other atmospheric parameters are in a comparable state of flux. However, the main surface features seem to be fairly well determined.

I. INTRODUCTION

The planet Mars has long been an object of mankind's investigations. Although Mars is the most easily studied of the planets, it remains one of the most perplexing. Unlike Venus, the atmosphere on Mars permits the surface conditions to be observed with relative ease. However, this comparative wealth of data has often led to confusion rather than enlightment. The values of such common terrestrial atmospheric parameters as surface pressure and composition are still highly uncertain.

The Martian atmosphere has one phenomenon which so far cannot be explained - the so-called "blue haze." This condition results in extinction in the blue region of the Mars spectrum, thus darkening or obliterating the planet's appearance in those wavelengths. The condition does not prevail universally; it has been observed to disappear planet-wide and then reappear within short time periods.

Although the origin of the observed surface features, as well as the composition of the surface material, presents additional problems, these must await the solutions of the problems of the Martian atmosphere.

II. SURFACE FEATURES

Mars has four general types of surface phenomena: the dark areas, the light areas, the polar caps, and the canals. While the appearance (and, indeed, the very existence) of the canals is rather unspecified, the optical properties of the other three features have been studied over long periods of time, and their appearances have been well established. The polar caps and dark areas go through seasonal fluctuations in size and color, but the light areas remain fairly constant. Much analysis has been done on these surface features, although their exact composition is still questionable.

A. Dark Areas

1. Characteristics

One of the first features on the Martian surface to attract attention was the dark areas. Much of this interest was aroused by color changes which appeared to be directly connected with seasonal cycles. These variations take the form of seasonal darkenings of the maria which proceed from the summer or warm pole toward the equator at a relatively uniform rate of about 35 km/day [1]. They appear to be unaffected by surface barriers or topography.

Many studies have been made to determine the nature of the soil. Polarization measurements show a powdery surface which is more absorbing than the surface of the light areas [2]. Pulverized limonite mixed with a powder of absorbing grains shows similar polarization characteristics. Seasonal data plus absorption characteristics seem to indicate the existence of animated microorganisms. Also, a relation between the geometrical albedo and wavelength is found to correlate with the reflection spectra of limonites.

However, several other theories on the composition of the surface of Mars have been postulated. For example, Arrhenius [3] has argued in favor of hygroscopic salt beds able to respond to small changes in atmospheric humidity. Others [4] have favored volcanic ash. One of the more interesting theories (Kiess, Karrer, and Kiess, Ref. 5) involved various phases of nitrogen oxides capable of migrating over the maria in order to explain seasonal changes. All of these proved inconsistent with additional observational data.

It has been argued that the seasonal darkening of the maria proceeds too rapidly and regularly to be a surface feature; thus, it has sometimes been thought to be either a movement of the atmosphere or diffusion through the atmosphere. However, in view of the fact that the surface temperature rises almost continuously from the very cold winter pole to the region around the summer pole, the warmest point on the planet;*

*There is disagreement on this conclusion.

it is difficult [1] to set up a circulatory system which would bring moisture from the summer polar regions all the way across the equator at a steady rate. On the contrary, any circulation system consistent with the postulated atmospheric thermal structure of Mars would tend to do just the opposite, i.e., directly oppose the darkening progression.

2. Organic or Inorganic?

The appearance of the maria has caused much conjecture about the existence of plant life on the Martian surface. There are several characteristics which seem to indicate vegetation. For example, Loomis [6] pointed out that parts of the dark areas which are covered by dust storms have some regenerative power and reappear, free from dust, in a matter of weeks or months. It is difficult to explain this phenomenon by an inorganic theory. Even glassy lava beds, possibly blown free of dust, would catch material in depressions, thus leaving only the points and obliterating the fields [5].

Sinton's discovery [7, 8] of bands in the Martian radiation spectrum near 3.5μ, which seemed to indicate the presence of organic molecules, increased the probability of the existence of plant life. Although carbonates also have bands in this region, they are eliminated by absorption details. The observed spectrum fits very closely that of organic compounds, particularly plants. A band at 3.67μ, at first unexplained, has been found in the alga cladophora, where absorption is apparently produced by carbohydrate molecules present in the plant. Thus, the evidence points not only to organic molecules, but to carbohydrates as well.

There are several objections to the plant theory. For example, photographs taken in red and infrared indicate that the maria do not reflect as if they contained chlorophyll [9]. This, however, is not a serious objection because many terrestrial plants known to contain chlorophyll do not possess the characteristic infrared spectrum because they have waxy coatings which obscure this spectrum. In addition, chlorophyll is not necessary, biologically, and there are many non-chlorophyll, anaerobic examples. Also, de Vaucouleurs [10] feels that the minute variations in humidity, which result from the melting caps, could scarcely trigger such conspicuous and large scale changes.

Despite this, the presence of vegetation still appears to be a more attractive explanation than any inorganic theory. If plants are accepted, then they must be extensive and active to explain the observed activity. Since great expanses of vegetation are required to be evident at the vast distances involved, large Martian plants are not ruled out, although the apparent lack of large amounts of water appears to favor a lichen-type of growth.

B. Light Areas

The light areas, like the rest of Mars, appear to be fairly smooth. Any existing mountains should have relief less than 2-5 km because of the lack of observable shadow [11]. The soil appears to be the same as that of the dark areas, possibly consisting of powdered limonite, $Fe_2O_3 \cdot nH_2O$ [1, 2]. However, some observers feel instead that felcite is present [10]. Silicates have also been suggested, but their characteristic infrared emission spectra have never been observed in the Martian spectrum. However, laboratory experimentation shows that silicates possess reduced emission characteristics as the grain size is reduced. Since silicates are far more likely to occur from a geological point of view, they quite possibly account for the bulk of the surface material [12]. The dust storms appear to be formed from the small particles which cover the light areas, since the spectral brightness coefficient for light areas observed during dust storms did not change [13].

Iron oxides on the surface may be the result of bombardment by asteroidal meteorites and their subsequent oxidation. Mars has a great number of asteroids crossing its orbit and has a collision expectation which is about 100 times that of Earth [14]. It has been estimated that Mars consists of an iron core surrounded by dunite, with a thin surface soil [15].

C. Caps

The caps of Mars were one of the first features to be discovered. They were first hypothesized to be ice deposits; and this remains the consensus today. It has been suggested that CO_2 deposits make up the caps, but this possibility is felt to be unlikely because, at Martian atmospheric pressure, the sublimation point of CO_2 is less than the temperature of the winter cap. Also, the reflection spectrum does not correspond to CO_2 [15].

In an attempt to explain this Martian phenomenon by the action of various phases of nitrogen oxides, it was thought that the caps might be sublimates of nitrogen tetroxide. The belts sometimes seen during the polar melting would then be higher oxides of nitrogen such as N_2O_3 and N_4O_6 [1]. However, the nitrogen oxides required for this theory have not shown up in measurements.

The reflection spectrum of the caps corresponds somewhat to ice, although no natural ice cap spectrum has been found to closely resemble the spectrum of Martian caps. Also, the caps do not reflect like hoarfrost or snow [16]. However, Kuiper showed that the infrared spectrum is similar to frost at low temperatures; Dollfus' polarization measurements confirm this [11]. Thus, there is significant evidence to indicate that the caps are water [10, 17]. Some feel that the polar caps are mainly an atmospheric rather than a surface phenomenon. They would then be a concentration of the haze material, probably ice needles [18].

D. Canals

After years of controversy about the possible existence of canals, it is now generally felt that they are a distinctive natural Martian surface phenomenon. Their exact form is still highly speculative. Some consider them to be continuous thin lines, while others think of them as a collection of dark points. From his observations, A. Dolphus concluded that the surface contains irregular spots grouped in various patterns which sometimes form straight lines. Another type of canal was discovered; they are thread-like, almost geometrically perfect, fairly short, and sometimes appearing in pairs [19].

The canals characteristically are dark lines which connect large dark sections. Where several canals meet, dark spots called knots or oases are observed. Individual canals undoubtedly represent boundaries between lighter and darker regions [19]. Also, adjacent bright areas appear to be separated by canals [3]. Seasonal changes in the canals seem to indicate vegetation. Many canals are almost invisible in the winter hemisphere. As spring approaches, they begin to reappear, first those adjacent to the caps, then those in the temperate zone, and finally those of the equatorial belt. One-half year later they disappear and in their stead a counter-wave of canal-darkening begins from the opposite pole. There is about a 10-15 day lag between cap melting and canal darkening. The oases are also hardly visible in the winter, but they grow with canal darkening [19].

There are different theories on the cause of the canals. Some think they are either a multitude of indistinquishable detail or perhaps humid places where vegetation appears [18]. Others feel that the canals are cracks in the surface, possibly of tectonic origin [14, 19, 20]. The oases would then be remnants of craters. If the soil is more fertile in the cracks, vegetation could develop there, rendering them observable and explaining seasonal changes. Settlement of this question must await further data.

III. SURFACE ATMOSPHERIC CONDITIONS

A. Temperature

The main temperature differences between Mars and Earth are due to the differences in the planetary water contents. Since there are neither oceans nor a significant greenhouse effect, most of the ground heat escapes after sunset and the nights are extremely cold [3].

One way of estimating surface temperatures is through radiative equilibrium considerations. A minimum may be obtained by assuming no atmosphere, and a maximum may be obtained by assuming a maximum greenhouse effect. This results in a range from 219 to 233° K, which is in reasonable agreement with thermal emission observations [21].

In making these computations, the minimum is calculated by assuming an atmosphere transparent to long-wave radiation. To compute the surface temperature the energy received from the sun is then equated to the energy emitted by the planet's surface. Utilization of an albedo of 0.15 yields 219°K. In calculating a maximum, the magnitude of the greenhouse effect depends essentially upon the amount of absorbing gas and the vertical temperature distribution. The average maximum surface temperature can be computed from the condition that the outgoing long-wave radiation at the top of the atmosphere must equal the incoming solar radiation (corrected for albedo). A linear temperature profile that would maximize the greenhouse effect is used, that is, the adiabatic lapse rate of -3.7° K/km. Atmospheric constituents are assumed to have constant mixing ratio with altitude. The values used for the absorbing gases are as follows: 4 percent carbon dioxide by volume, 10^{-2} cm of precipitable water, and 0.15 cm STP of ozone. The outgoing radiation fluxes at the top of the atmosphere are found by use of Elsasser's equations and radiation tables (1960). The resulting surface temperature is 233°K, which indicates a small greenhouse effect compared to Earth's [21].

Mean temperature values may also be obtained from extrapolation of thermal emission data. The following estimation is based on average noontime latitudinal temperature profiles for the different seasons obtained by Gifford in 1956. A planetary mean temperature of 233°K may be found by extrapolation to the poles, averaging the seasonal data into an annual curve, correcting the annual curve for the amplitude of the diurnal temperature variation (equatorial temperature assumed to be 303°K decreasing with latitude according to a cosine law) and then computing an area-weighted mean temperature from the resulting annual curve. This analysis also indicates an average equatorial temperature of about 240°K and an average polar temperature of about 200 to 210°K [21].

Compiled observations indicate that the best single value for surface temperature is about 230°K. However, Mintz concluded that extension of Earth dry desert experience indicates that the air temperature a few meters above the surface can be as much as 50°K cooler than the surface temperature [22].

B. Pressure

Until fairly recently, the surface pressure of Mars was felt to be well established, with most observers agreeing on a value of about 85 mb. Dollfus' polarimetric estimate, corrected for self-absorption, gave a value of about 87 mb, and the other estimates fell in about this range [23]. However, Kaplan, Münch, and Spinrad [24] used a Mt. Wilson high dispersion spectrogram to derive a pressure much lower than previous figures. Values of $14 \pm 7\mu$ precipitable water and 55 ± 20 m atm carbon dioxide were indicated by detected rotational lines of H_2O near λ 8300 and carbon dioxide near λ 8700. The absence of oxygen from the spectrum set an upper limit of 70 cm-atm for that potential constituent. By combining the carbon dioxide amount with Kuiper and Spinrad's observations of the strongly saturated bands in the 2μ region, a surface pressure of 25 ± 15 mb has been obtained. Also, re-interpretation of Kuiper's old observations (1949) indicates a value which would fall in the derived range. Kaplan feels that previous estimates were incorrect because the methods used assumed that all the light scattering was by small particles [11].

There has been sharp disagreement with their value, however. Öpik feels that if his haze version is correct, then the surface pressure should be increased about 50 percent because of absorption effects. This contradicts Kuiper who says that any haze which scatters light almost as much as the gas molecules do would lead to an excessive pressure estimate. In addition, de Vaucouleurs states that he has allowed for effects of particle scattering in his value of 85 mb and feels his estimate was confirmed by Dollfus' measurements [10].

Surface pressure estimates are difficult to evaluate, since there are a number of assumptions which are generally made. The values are really estimates of the mass of air per unit column, and they are usually based on one or more of the following assumptions: The very first-order solution to the equation of radiative transfer is adequate and a homogeneous model is sufficient, because the Martian atmosphere is optically thin; the solid surface of the planet reflects sunlight according to simple laws that can be deduced from astronomical observations and laboratory measurements of terrestrial surfaces; the atmosphere scatters and polarizes according to Rayleigh's Law; the effects of the solid surface and the atmosphere are simply additive; haze particles represent minor perturbations of the reflected light, and their effects can be truly judged from lab tests on terrestrial particles; or haze particles may strongly absorb, but their angular scatter still conforms to the Rayleigh pattern. Any of these assumptions may be wrong, and thus, pressure estimates could easily be off ±50 percent or more [25].

In any case, present pressure values are in a state of flux, with estimates being made on the order of 10 mb as well as on the order of 100 mb.

C. Constituents

1. Carbon Dioxide

The first element detected in the Martian atmosphere was CO_2. Interpretation of the spectrogram of Kaplan, Spinrad, and Münch [24, 26] places the CO_2 abundance at 55 ± 20 m atm. The probable error results from uncertainty in the equivalent width measurements.

2. Carbon Monoxide

It has been proposed that CO_2 photodissociation plus oxygen escape would produce considerable CO concentrations. This should give rise to a band at 2.35 microns [13]. However, Sinton's infrared spectrophotometric scan (1959) shows no strong feature near this band, thus setting an upper limit of 10 cm-atm [27]. There are several factors which could lower CO concentration [23]. A possible reaction is (Urey - 1959) $CO + CO \rightarrow CO_2 + C$. This can occur at low temperatures with suitable catalysts, but it cannot occur in the free atmosphere and is probably negligible. A more feasible mechanism involves the ionized state of CO, in which its effective weight would be reduced by one-half due to the electrostatic field created by outward electron diffusion. Other possible CO sinks are [27]: $CO + O + M \rightarrow CO_2 + M$, where M is any third body; and $2\ CO + h\nu \rightarrow C_2 + 2O$. The first reaction would prevent gigantic accumulation, and the carbon smoke in the second has been suggested as an explanation of atmospheric haze. However, if there is more than 0.3 cm-atm of O_2 present, CO_2 will be largely protected from photodissociation [27].

3. Oxygen

Kaplan, Spinrad, and Münch [24] did not detect any Doppler shifted components to the telluric bands in the O_2 bands near λ 7600. It is estimated that any Martian lines stronger than 20 mÅ would have been visible. An upper limit of W $(O_2) \leq 70$ cm atm is arrived at. Marmo and Warwick [3] have estimated an abundance of oxygen at about 0.2 cm-atm, with maximum concentration occurring between 110 and 160 km. This would produce at least some shielding.

4. Ozone

Ozone forms at high altitudes on Earth due to the absorption of solar radiation by O_2 in the region of 1760-1925 Å as follows:

$$O_2 + h\nu \rightarrow O_2^* \quad \text{and} \quad O_2^* + O_2 \rightarrow O_3 + O,$$

which is then carried downward by turbulent mixing [28]. On Mars, this reaction should occur over a longer interval of depth. The radiation in the 1250-1760 Å region should be able to penetrate deeper into the Mars atmosphere due to lack of absorbent O_2, and the following series should occur: $O_2 + h\nu \rightarrow O + O$ and $O + O_2 + M \rightarrow O_3 + M$. Thus, ozone should be formed from oxygen atoms at all levels up to 10^{-2} mb, which is the minimum pressure for a 3-body collision process. Marmo and Warwick [3] calculated ozone abundance on a basis of CO_2 concentration only, and arrived at a maximum of 10^{-4} cm-atm. They also concluded that ozone abundance would not pass through a maximum, but would increase with decreasing height. This is in accord with Wildt's theory that the surface is highly oxidized.

5. Nitrogen

The difference between the complete pressure and the partial CO_2 pressure is probably almost entirely due to argon and nitrogen [24]. N_2 is thought to be the bulk constituent, because most of the other gases, with the exception of the inert gases, are either too light or too photochemically reactive to be retained [3]. Terrestrial analogy would place N_2 at about 95 percent by volume.

6. Argon

Argon, with its atomic weight of 40, its characteristic inert nature, and its relative cosmological abundance, could possibly predominate in the Martian atmosphere. Brown and Suess independently concluded that within the proposed age of the universe, 10^9 years, argon could have become the major Martian atmospheric constituent. Despite this, model atmospheres generally contain only 4-5 percent argon [3]. It is felt that some argon must be present due to the decay of potassium 40 [11]. It is interesting to attempt to estimate the argon content by analogy with Earth conditions. If it is assumed that the net A^{40} content of the Martian atmosphere is the same as that of Earth (Brown-1952, Urey-1958), then a partial pressure $P_a♂(A) = 19$ mb is found. If the argon content of Mars is to that of Earth as the ratio of the corresponding planetary masses, then $P_b♂(A) = 2$ mb [24].

7. Water

Indications of Martian water have been found through polarization methods [29] and by theoretical estimates based on consideration of the Martian greenhouse effect [15, 30], but actual measurement did not occur until the spectrogram of Kaplan, Spinrad, and Münch [24]. They estimated $14 \pm 7\mu$ of precipitable water in the atmosphere.

8. Oxides of Nitrogen

Another possible constituent which has been proposed, generally in an attempt to explain various observed features, has been oxides of nitrogen [1]. However, interpretation of measurements show that there can be no more than trace amounts of such elements present [25].

IV. THE BLUE HAZE

The Martian atmosphere normally appears hazy if it is observed in the blue region of the spectrum. The contrast is quite significant because the albedo, which is 0.3 at 7000 Å, drops to 0.04 for $\lambda < 4500$ Å [27]. This opaque veil covers the entire planet and is referred to as the blue haze. The apparent redness of Mars is due to the properties of the haze, not the properties of the surface [14].

Blue clearings have been noted, in which the wavelength at which opacity begins becomes shorter, although the haze is always present to some extent [22]. Both partial and planet-wide clearings have been observed. Partial clearings at the center seem to be common. Also, it appears that the larger the clearing, the greater the transparency. Complete clearings have occurred in about four hours [31].

There are several models which attempt to explain the blue haze. Some possible phenomena which would explain the opacity are surface changes, atmospheric dust, CO_2 or H_2O, nitrogen oxides, carbon "smoke," meteoritic effects, and auroral emissions [31].

a. Surface Changes

Mars is not featureless in blue light, but shows outlines readily identifiable at longer wavelengths. Thus, it was at first thought that the effect might be due to surface properties. However, simultaneous photographs made at longer wavelengths at the time of a blue clearing failed to show contrast changes. The haze was then concluded to be atmospheric, but perhaps not entirely so, because Hess (1941) and Tombaugh (1954) observed marked color changes in some of the dark areas beginning with and following clearings. Hess felt this indicated vegetation, assuming that the temporary ultraviolet exposure caused by a clearing produced color changes in organic substances [31]. However, photometric studies in red, blue, and green result in none of the expected correlation which would indicate solely an atmospheric change, i.e., no variation in contrast between the surface features [32].

b. Atmospheric Dust

It has been proposed that dust particles could cause the haze by Rayleigh scattering [16, 33]. A particle size of 0.15 - 0.20 microns has been suggested [34]. This is based on the assumption that extinction is caused by forward scattering. However, Goody [35] and Öpik [23] have pointed out that such a purely forward-scattering layer above a reflecting surface is transparent, since the scattered light will be reflected back by the surface and then forward-scattered out of the atmosphere. In any case, with the particle sizes involved it is difficult to explain blue clearings. Stoke's law for the rate of settling, $V = 2/9\ r^2 \rho g/\mu$ where r = radius of spheres, ρ = density, and μ = coefficient of molecular viscosity of the medium, shows that it would take years for such size particles to settle out from even a one-kilometer altitude [34]. However, the dust cloud could be absorbent [35] or it could have a small back-scattering lobe. In the latter case, the small amount of blue radiation reflected by the surface albedo of about 0.05 would be swamped by back-scattered solar radiation in the blue if more than 5 percent of the incident solar radiation is initially back-scattered, thus obscuring surface features. In any case, a dust theory fails to explain why a clearing occurred during the 1956 opposition, in spite of extensive dust storms which obscured much of the surface [22].

c. Meteoritic Effects

Link has suggested that the haze is caused by dust of a meteoritic nature [27]. This opens up new possibilities for haze constituents, as particles swept up from space include those detected in cometary spectra [31]. These are ammonia, methane, and water ices mixed with meteoritic materials composed of nickel, iron, and other elements [36].

d. Auroral Emissions

Auroral emissions or some type of airglow would account for some of the haze, since such emissions could reduce the general contrast. The clearings could be due to the control of the airglow emission rate by temperature. It would also be caused by fluctuations in the CO and O concentrations [37]. Sagan raised the following objections to auroral models: All observers agree that the blue haze is at an altitude of less than 200 km, but to reach such depths, protons must have improbable energies and fluxes; and to explain observed duration of clearings, impossibly low interplanetary magnetic fields are required [27].

e. Carbon "Smoke"

Rosen has pointed out that carbon particles formed from CO_2 and CO photodissociation may cause the haze [31]. Öpik follows in this line, feeling the haze to be an absorbing smoke which is black in reflection and red in transmission. The clearing would be explained by variations in the smoke content, since small fluctuations may cause large changes in the marginal visibility of the surface [14, 23]. However, it is difficult to see how this could cause a planet-wide clearing.

f. Nitrogen Oxides

Kiess et al. [9] attempted to explain the haze by variations in the $2\ NO_2 \rightleftarrows N_2O_4$ system. A clearing would require a small warming of the lower atmosphere which would lead to a small decrease in the number of yellow N_2O_4 particles present [1]. There are several difficulties with this model. Since N_2O_4 is a fairly reactive compound, it appears unlikely that it would be a survivor of the primitive Martian atmosphere. If present, it would most likely have to be continuously generated from its constituent elements [38]. Another difficulty is in the thermodynamic instability of the oxides of nitrogen. In addition, lack of absorption bands in the Martian infrared spectra indicates that the maximum nitrogen oxide concentration in the atmosphere is about 1.2 parts per million, certainly insignificant [39].

g. Atmospheric Carbon Dioxide

Carbon dioxide particles have been suggested as an explanation [40, 41]. In this case, a blue clearing would indicate an evaporation. However, it is felt that CO_2 clouds would be much too opaque, and that the temperatures required to freeze CO_2 occur only at very high altitudes [34]. Also, the following objections have been raised by Urey [31] against all theories which attempt to explain the haze by condensable substance:

1. The low probability that a condition of uniform condensation would exist at all latitudes in a convecting and rotating atmosphere suggests that weather bands parallel to the Martian equator should be evident in blue photographs, but these are not observed.

2. To cause a planet-wide clearing, the temperature must rise simultaneously and uniformly over the entire planet, a rather unlikely event.

3. The disk of Mars should be flattened more in blue light than in red light, because according to Hess's model the altitude of the haze layer must decrease with latitude, but the flattening is not observed.

h. Atmospheric Water

A similar model has been proposed, involving water crystals instead of CO_2 crystals [42]. Urey's objections apply, but it has been noted that Mars may not have to have weather bands. This is because the low density could cause the atmosphere to diffuse rather than circulate [31]. The necessity of planet-wide temperature changes still exists, but observations indicate that partial clearings are common [43] with planet-wide clearings being relatively rare, in agreement with theory. Another objection is that photoelectric measurements show Mars to be black in the ultraviolet, unlike ice crystals [10]. Also, if the effect is due to absorption, then concentrations of the haze should be relatively dark. The blue clouds are believed to be ice crystals, but they are observed to be relatively bright [27]. This theory is quite attractive by Earth analogy, however. Terrestrial noctilucent clouds at 80 km may be the equivalent of Martian blue clouds, and noctilucent clouds have been recently determined to be composed of ice crystals. In fact, the Earth may have a blue haze, which would be unobservable from the surface [31].

For a while it was thought that there was a correlation between clearings and Earth-Mars oppositions. This suggested some optical explanation for the clearings, some phenomenon similar to the brightening of terrain when viewed along the illuminating rays. However, it was found that clearings were not confined to oppositions [44], and that the apparent correlation was simply due to the fact that Mars has never been observed systematically except in the few weeks before and after opposition [31]. In fact, some of the outstanding characteristics of the haze are its uniformity and apparent lack of correlation to anything. There appear to be no weather bands; and no correlation has been found between opacity and latitude, opacity and solar activity, or clearing and angular heliocentric separation between Earth and Mars [3].

It is possible that the blue haze causes the Wright effect, which is the observed increase in the Martian planetary diameter in blue light over that in red light [31].

V. ATMOSPHERIC CONSTRUCTION

a. Clouds

Clouds can be readily observed in the Martian atmosphere. They are divided into three types: white, yellow, and blue. The yellow clouds appear to be dust, and the blue and white clouds are probably ice crystals [5, 15, 27, 38]. The identity of the blue and white clouds is suggested by polarization studies [38], with the two types differing only in the size of their crystals [27]. The blue clouds probably consist of crystals ranging from 0.1 to 1.0 microns in diameter, and the white clouds probably have crystals which are about 1.0 micron in diameter [15].

Mists which are observed over the poles have an albedo of around 0.3, which is incompatible with ice clouds. However, it is possible that this is not Ice I, but is a low temperature modification with different absorption coefficients [27].

b. Circulation

The dry atmosphere is 70 - 75 percent transparent in the far infrared; therefore, the amount of heat radiated from the equator is much more than that radiated from the poles. This results in a relatively light heat load and keeps the Martian atmosphere in a symmetrical regime much of the time. However, this refers only to the yearly average, since the small surface heat capacity leads to great seasonal changes [27]. A large diurnal change is also conceivable. Mintz recognized the possibility of such a change through the troposphere which could produce a diurnal thermal tide or period of considerable amplitude in the general tropospheric winds [21]. It has been suggested that the Martian atmosphere is Earth-like in spring and autumn and is uniquely Martian in summer and winter. Terrestrial circulation consists of heat transfer from equator to both poles via circulating air masses, but the strong Martian north-south temperature gradient in summer and winter would cause heat to be transported directly from the warm to the cool pole [3]. Of course, it is also possible that the low atmospheric density would cause the atmosphere to diffuse rather than circulate [31].

c. Atmospheric Temperature

Even a small amount of oxygen could give rise to ozone, and thus appreciable amounts of stratospheric heating could occur [45]. The temperature of the upper atmosphere would be largely determined by the absorption of solar ultraviolet [28]. Some possible reactions for ozone heating are as follows:

$$O_2 + h\nu \rightarrow O + O, \quad O + O + M \rightarrow O_2 + M$$

$$O + O_2 + M \rightarrow O_3 + M,$$

$$O_3 + O \rightarrow 2O_2,$$

$$O_3 + h\nu \rightarrow O_2 + O,$$

where M is an arbitrary third body, primarily N_2. Calculations for this process indicate a maximum increase of 0.33 °K, occurring at forty kilometers [21], but other observers feel higher values are possible [45].

It is felt that the CO which must be present acts as a thermostat in the upper atmosphere, keeping the temperature at escape level (1500 km) from exceeding about 1100 °K. If it were not for this cooling, the upper atmosphere would form such an extensive and effective thermal insulation between the upper ionosphere and the heat sink at the mesopause that the temperature would probably exceed 2000 °K, assuming no radiative loss. However, CO radiates as follows (Bates - 1951):

$$R(Z) = N^2(Z)\ f(CO_2)\eta\ h\nu\ e^{-h\nu/KT}$$

where

f is the fraction by volume of CO_2

and

$\eta \cong 10^{-14}$ cm^3/sec = rate coefficient for deactivation.

However, $f(CO_2) = 2 \times 10^{-2}$. Equilibrium is maintained at 1100 °K [45].

In the mesosphere the temperature is a constant 134°K above 90 km. The mesopause is at a temperature of about 76°K [46].

d. Ionospheric Reactions

There are many different sequences which could occur between ions in the Martian atmosphere. For example, possible O^+ and N_2^+ recombination would occur as follows:

$$N_2^+ + \bar{e} \rightarrow N + N$$

or

$$O^+ + N_2 \rightarrow NO + N$$

followed by

$$NO^+ + \bar{e} \rightarrow N + O$$

[4]. In consideration of recombination electron loss, the main processes would be

$$xy^+ + \bar{e} \rightarrow x + y \text{ (dissociative recombination)}$$

and

$$xy^+ + \bar{e} \rightarrow xy + h\nu \text{ (radiative recombination).}$$

Despite the fact that dissociative recombination is much faster than radiative, the ions recombine radiatively unless they can undergo reactions such as

$$x^+ + yz \rightarrow xy^+ + z \text{ (atomic-ion exchange)}$$

and

$$x^+ + yz \rightarrow yz^+ + x \text{ (charge exchange)},$$

followed by dissociative recombination of the resulting molecular ion. CO^+ and CO_2^+ will probably be lost by dissociative recombination. The lack of oxygen will prevent O_2 shielding, and thus solar radiation could have a large effect deep in the atmosphere [47, 48].

VI. CONCLUSIONS

The landscape of Mars has been fairly well established, but the surface characteristics and composition of the atmosphere is still largely unknown. Such basics as temperature and pressure are quite uncertain, and most of the constituents have not been identified. The blue haze is another mystery, whose solution must await more reliable data.

The proposed low atmospheric pressures and densities could have a significant effect on the design of a Mars spacecraft. Such concepts as a glider landing vehicle may no longer be feasible.

Man's exploration of this planet will advance meteorology a gigantic step, for the comparison of two different planetary atmospheres will prove invaluable.

APPENDIX A

ATMOSPHERIC PARAMETERS OF MARS

Parameter	Max	Min	Most Probable
Diurnal Mean Surface Temperature	300°K	200°K	230°K
Surface Pressure	135 mb	10 mb	25-40 mb
Density (Surface)	1.488×10^{-4}	2.26×10^{-5}	1.28×10^{-4} gm/cm^3
Surface Wind Velocity	60 km/hr	mild	10 km/hr
Water Content	0.01 gm/cm^2	trace	$1.4 \pm 0.7 \times 10^{-3}$ gm/cm^2
CO_2 Content	60%	.55%	2%
N_2 Content	98%	40%	94%
Argon Content	30%	trace	4%
Oxygen Content	.06%	trace	.04%
Molecular Weight	39	28	28.8
Tropopause	24 km	11 km	17 km
Lapse Rate (Troposphere)	-4.170 °K/km	-3.636 °K/km	-3.7 °K/km

(References: 3, 10, 11, 17, 25, 47, 49, 50, 51, 52, 53, 54).

APPENDIX B

EVALUATION OF THE SPECTROSCOPIC MEASUREMENT OF KAPLAN, MÜNCH, AND SPINRAD [54, 55, 56]

1. Abundance

A critical review of the spectroscopic measurement of Kaplan, Münch, and Spinrad has been made. There appear to be several instances where the actual uncertainties are somewhat larger than were indicated in the original report. These are listed below.

a. The Rank Calibration: Rank's laboratory calibration of the 8689 Å band was used to obtain CO_2 band intensities. No uncertainty was assigned to the value used by Kaplan et al., but Rank considers the accuracy of his intensity measurements to be 6 percent at best. However, he agrees with the CO_2 abundance values derived by Kaplan.

b. Although no range of uncertainty was ascribed to the effective air mass of the Mars atmosphere, Münch now feels that a correction suggested by Ohring is valid, viz the value should be changed from 3.6 to 3.9. The correction includes the use of the proper value of the angle between the Earth and the Sun seen from Mars, a more precise expression for the variation of air mass with zenith angle, and a slightly greater seeing motion smear. The change in air mass slightly reduces the CO_2 abundance and increases the pressure. Considering no other effects, the surface pressure is changed from 25 to 28 mb.

c. A temperature of 230°K is used, but it seems unlikely that the Martian atmospheric temperature is that high at the effective absorbing level, so the amount of CO_2 corresponding to about 200°K is to be preferred. Münch has confirmed this and suggests that the temperature may be as low as 185°K.

d. The method used for correcting the laboratory data to Martian conditions is not certain. Kaplan, who is out of the country, performed this part of the analysis and the other authors are not sure of his procedure. Independent calculations have led to different results.

By correcting the laboratory data to NTP and using the new value for air mass, a preliminary CO_2 abundance of 43 ± 25 m atm has been obtained. Some assumptions are made about probable errors in the laboratory data.

2. Pressure Estimation

This section is concerned with an evaluation of the pressure estimate made in the work of Kaplan et al.

The authors give no range of uncertainty for the equivalent air mass measured by Sinton. They use 1.86 but Sinton's paper indicates a value of 1.82 ± .32. This uncertainty must be factored into the total uncertainty given for the pressure. The effect is to reduce the surface pressure somewhat, but the value of the latter is heavily dependent on the CO_2 abundance.

Some independent estimations of pressure have been made. The analysis of Kuiper and Owen which gives a surface pressure of 17 ± 9 mb is under review, as is Moroz's article on the spectrum of Mars. Moroz derived a surface pressure of 15^{+15}_{-5} mb.

Kaplan et al. made three calculations of the Martian surface pressure, all of which used the CO_2 abundance obtained from the absorption measurements at 8700 Å in conjunction with the pressure dependent strong band absorption in the 2μ region. The method used appears sound, but a correction should be made to account for the temperature dependence of the absorption coefficient. Somewhat higher pressures would then be obtained, since the pressure is inversely proportional to the CO_2 abundance. By combining what is felt to be the correct temperature dependence with reasonable estimates for the uncertainty of basic measurements, the following pressure values were obtained. Calculations using Sinton's 2μ data gave 35 ± 32 mb, Kuiper's 2.06 data using equivalent widths yielded 43 ± 34 mb, and Kuiper's 2.06 data using laboratory comparison resulted in 26 ± 23 mb. These values are critically dependent on the CO_2 abundance determination.

APPENDIX C

TABULATION OF PHYSICAL CHARACTERISTICS OF MARS

Mean Distance From Sun (A)	1.523691 A.U.
Inclination of Orbit to Ecliptic (I)	1.84991 deg
Eccentricity of orbit (e)	.093372 (1964)
Mean Daily Motion (η)	.524033 deg/sid. day
Mars Orbit to Mars Equator	25.20 deg
Mean Orbital Velocity	24.13 km/sec
Mean Solar Constant	.840 cal/cm^2 min
Sidereal Year	686.980 Earth Sidereal Days
Mean Synodic Period	779.935 Earth Sidereal Days
Mass	.642 x 10^{27} gm
Bulk Density	4.04 gm/cm^3
Mean Surface Gravity	375 cm/sec^2
Radius (Equator)	3374 km
Albedo (Integrated)	0.25
Perihelion Distance	1.381428 A.U.
Aphelion Distance	1.665954 A.U.
Sidereal Day	24 h 37 m 22.668 s
Solar Day	24 h 39 m 35.247 s

(References: 3, 10, 15, 17, 51, 57).

APPENDIX D

AN EVALUATION OF PRESSURE ESTIMATES FROM POLARIMETRIC OBSERVATIONS [54]

Several studies of surface pressure have been based on polarimetric observations. Results of about 100 mb are usually obtained, and these are often used as a reference for relatively high surface pressure values.

The following assumptions are commonly made in these studies: The Martian atmosphere is devoid of any scatterers aside from the molecules which make up the atmospheric gases, and there is no multiple scattering in the atmosphere and no addition to light scattered from the atmosphere by light reflected from the surface. For a precise treatment, the following sources which can contribute to the illumination from a planet and to the polarization should be considered.

1. Rayleigh backscattering from atmospheric scattering.

2. Rayleigh type backscattering from very fine particles.

3. Mie backscattering from aerosols.

4. Surface reflection of diffused radiation.

5. Rayleigh forward scattering of radiation from (4) by atmospheric gases.

6. Rayleigh type forward scattering of radiation from (4) by very fine particles.

7. Mie forward scattering of radiation from (4) by aerosol particles.

8. Multiply scattered radiation.

Consideration of such factors produces large fluctuations in pressure estimates based on polarimetric studies. For example, a pressure of 114 mb is obtained if one uses Dollfus' polarimetric study and assumes an atmospheric composition similar to that of Earth. However, this pressure is changed to 60 mb if one assumes a pure CO_2 atmosphere.

The fluctuation is even greater if aerial suspensions of very fine particles are assumed. Such particles may form the blue haze. They would behave as Rayleigh particles, giving a polarization similar to that of molecules but scattering more efficiently. Choosing a particle size of $r = 0.1\mu$ with refractive index $n = 1.33$ (= H_2O ice), it is found that 3.6×10^8 particles per cm^2-column will suggest the observed pressure of 114 mb but that the true pressure will be only 20 mb. In this case, the atmosphere was assumed to be pure nitrogen, but an increase in the CO_2 content would tend to reduce the particle requirements, which in any case are not unreasonable. Since there is no method of remotely distinguishing molecules from particles in this size range, it appears impossible to establish a reliable surface pressure based only on polarimetric studies.

SCHEMATIC MAP SHOWING THE
DISTRIBUTION OF DESERTS AND MARIA [58]

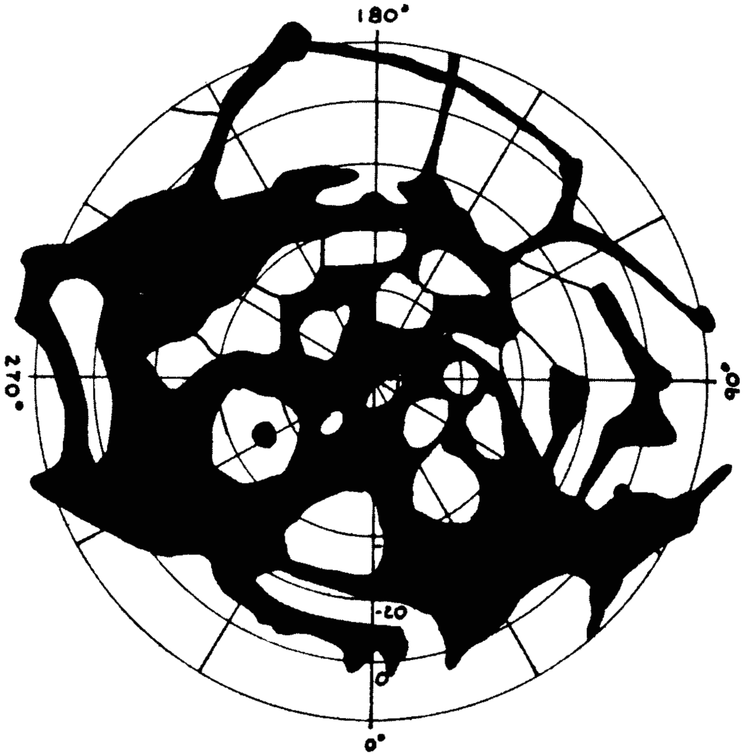


Fig. 1. Southern hemisphere

maria

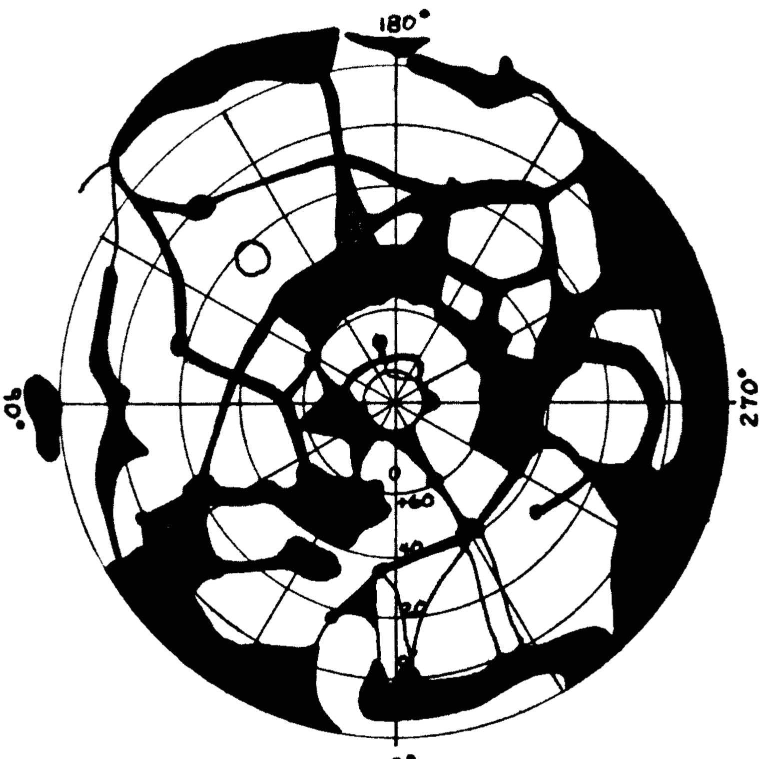
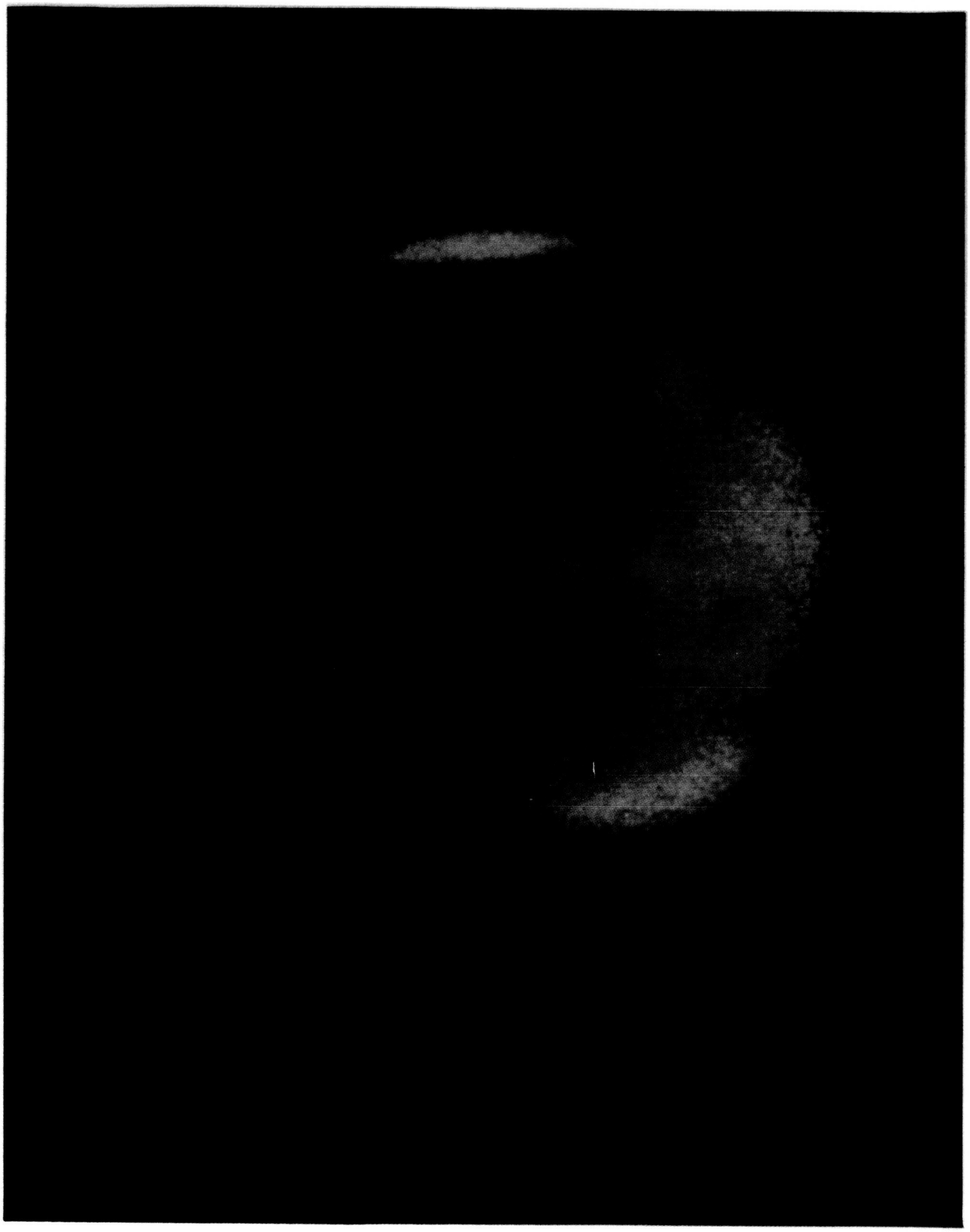
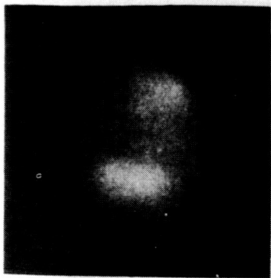


Fig. 2. Northern hemisphere

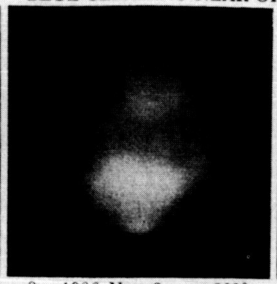


MARS: Produced by Kodak Dye Transfer Process. Reproduced by permission from the Lowell Observatory from MARS by E. C. Slipher.

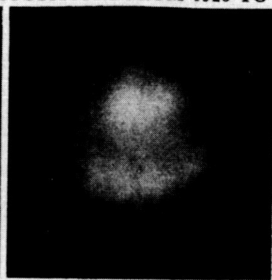
BLUE CLEARING NEAR OPPOSITIONS FROM 1926 TO 1958



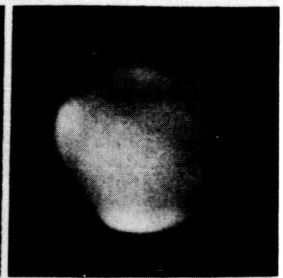
1. 1926 Nov 1 $\lambda333^\circ$
U.T. 7:43 Aug 4 M.D. B



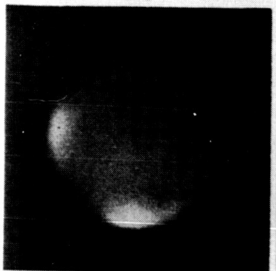
2. 1926 Nov 3 $\lambda329^\circ$
U.T. 8:41 Aug 6 M.D. B



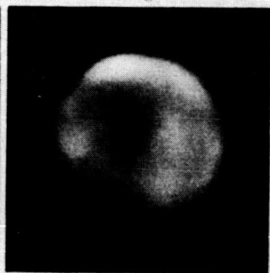
3. 1926 Nov 5 $\lambda342^\circ$
U.T. 10:44 Aug 7 M.D. B



4. 1928 Dec 29 $\lambda330^\circ$
U.T. 9:33 Sept 28 M.D. B

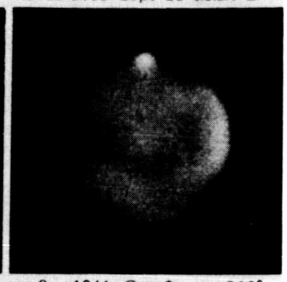


5. 1928 Dec 29 $\lambda336^\circ$
U.T. 9:57 Sept 28 M.D. B

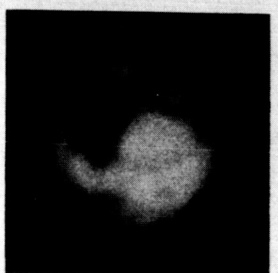


6. 1937 May 21 $\lambda295^\circ$
U.T. 6:20 Feb 20 M.D. B

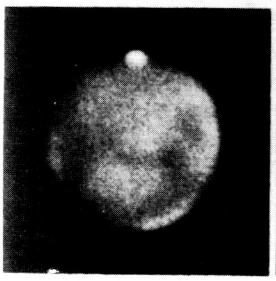
7. 1937 May 22 $\lambda321^\circ$
U.T. 8:43 Feb 20 M.D. B



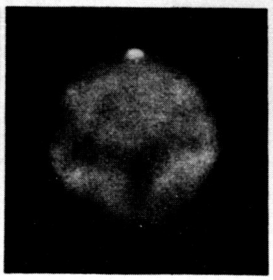
8. 1941 Oct 9 $\lambda346^\circ$
U.T. 7:46 July 10 M.D. B



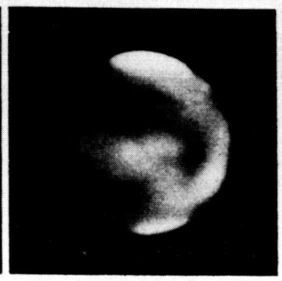
9. 1937 May 21 $\lambda305^\circ$
U.T. 7:41 Feb 20 M.D. Y



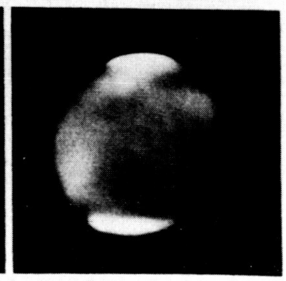
10. 1941 Oct 10 $\lambda334^\circ$
U.T. 7:27 July 11 M.D. B



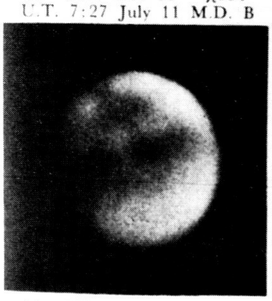
11. 1941 Oct 11 $\lambda293^\circ$
U.T. 5:15 July 11 M.D. B



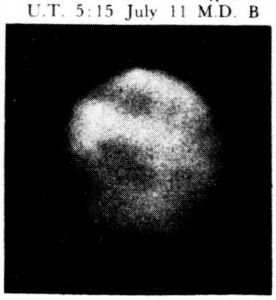
12. 1954 June 14 $\lambda255^\circ$
U.T. 23:08 Mar 19 M.D. B



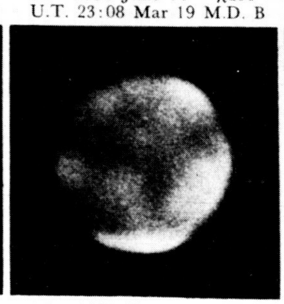
13. 1954 July 25 $\lambda219^\circ$
U.T. 21:02 Apr 13 M.D. B



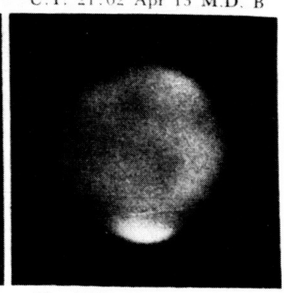
14. 1956 Sept 1 $\lambda345^\circ$
U.T. 21:52 June 4 M.D. B



15. 1956 Sept 3 $\lambda331^\circ$
U.T. 22:07 June 6 M.D. B



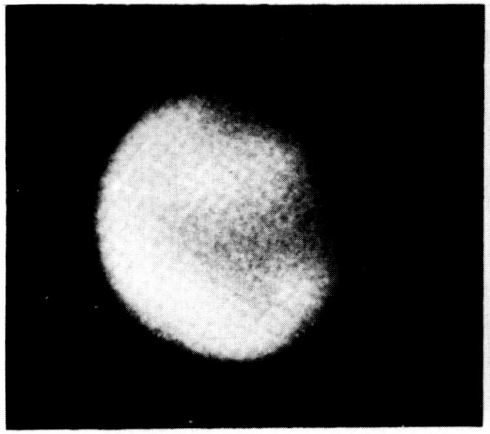
16. 1958 Nov 13 $\lambda279^\circ$
U.T. 5:08 Aug 17 M.D. B



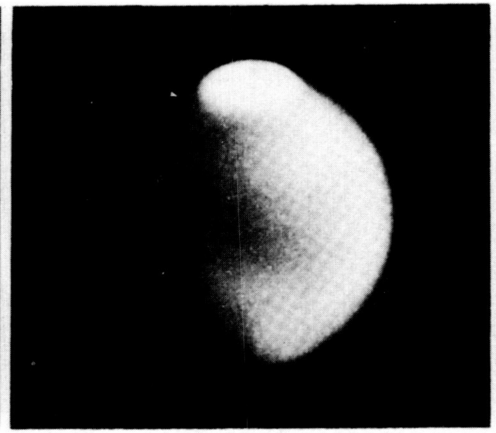
17. 1958 Nov 14 $\lambda273^\circ$
U.T. 5:18 Aug 17 M.D. B

Examples of blue clearing for various periods of opposition. The center photograph is taken in yellow light for comparison. Reproduced by permission of Lowell Observatory from MARS by E. C. Slipher.

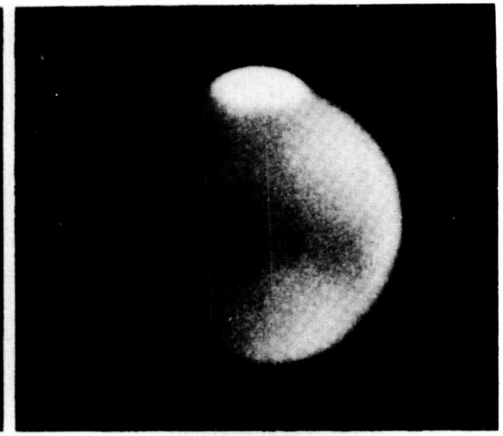
EXAMPLES OF BLUE CLEARING FAR FROM OPPOSITION



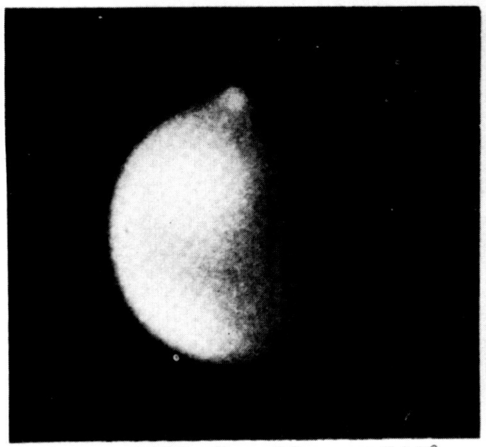
1. 1941 Nov 22 λ250°
U.T. 3:38 B
Aug 6 M.D.



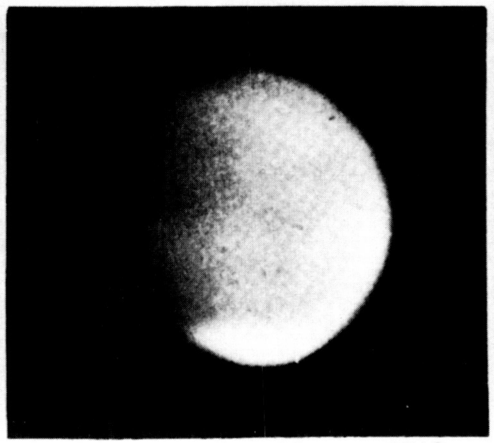
2. 1956 Aug 7 λ264°
U.T. 0:59 B
May 19 M.D.



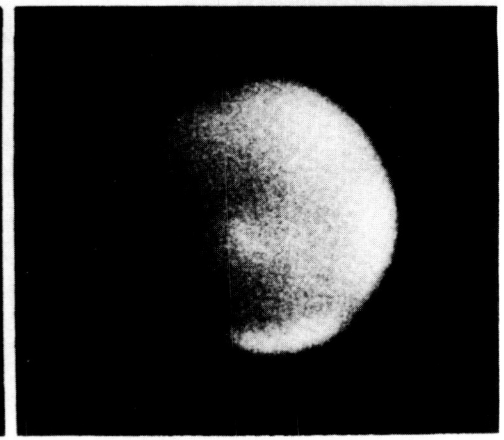
3. 1956 Aug 11 λ245°
U.T. 2:11
May 21 M.D.



4. 1956 Oct 26 λ311°
U.T. 4:09 B
July 10 M.D.



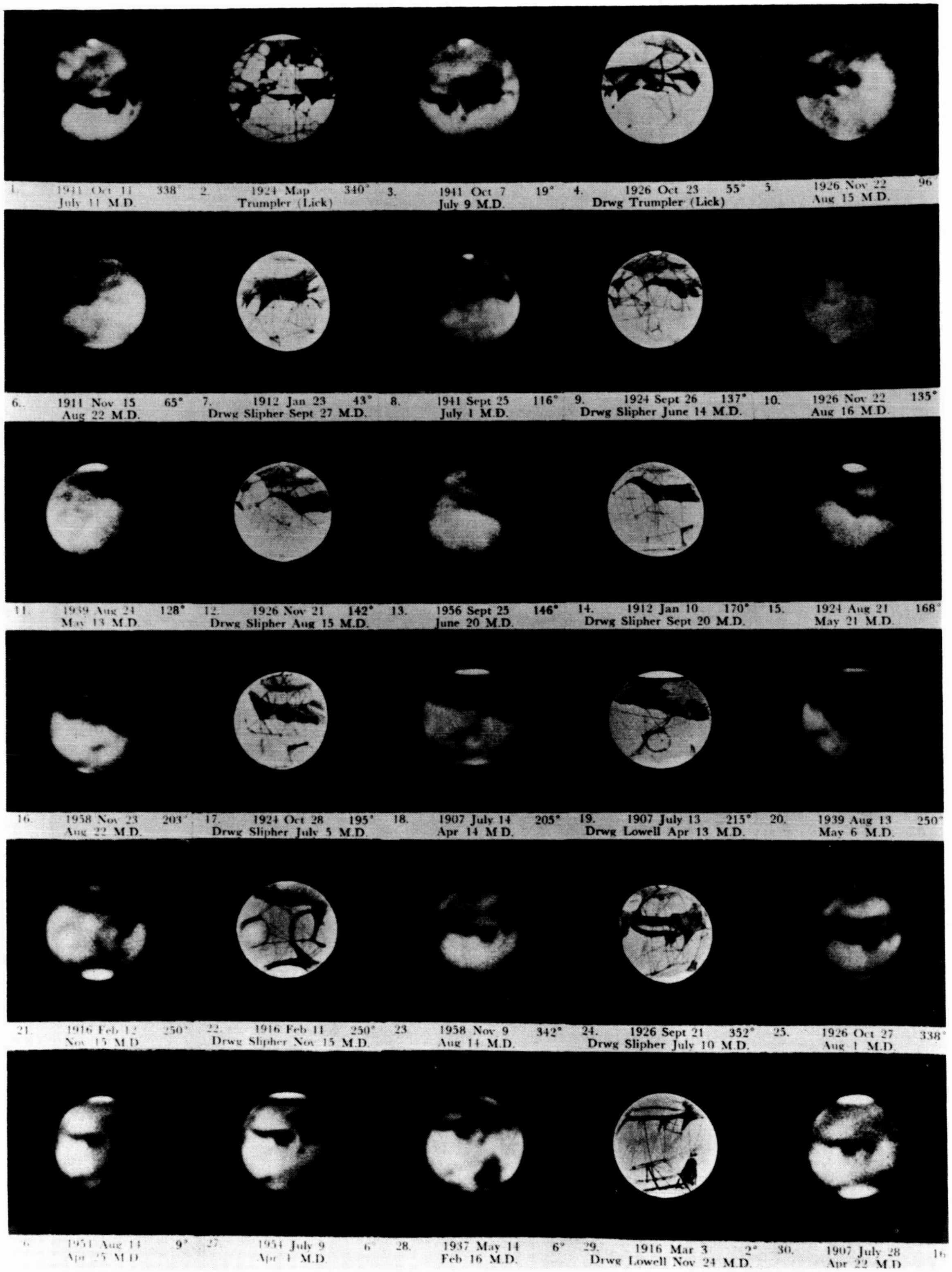
5. 1958 Oct 13 λ271°
U.T. 10:18 B
Aug 17 M.D.



6. 1958 Oct 15 λ255°
U.T. 10:30 B
July 31 M.D.

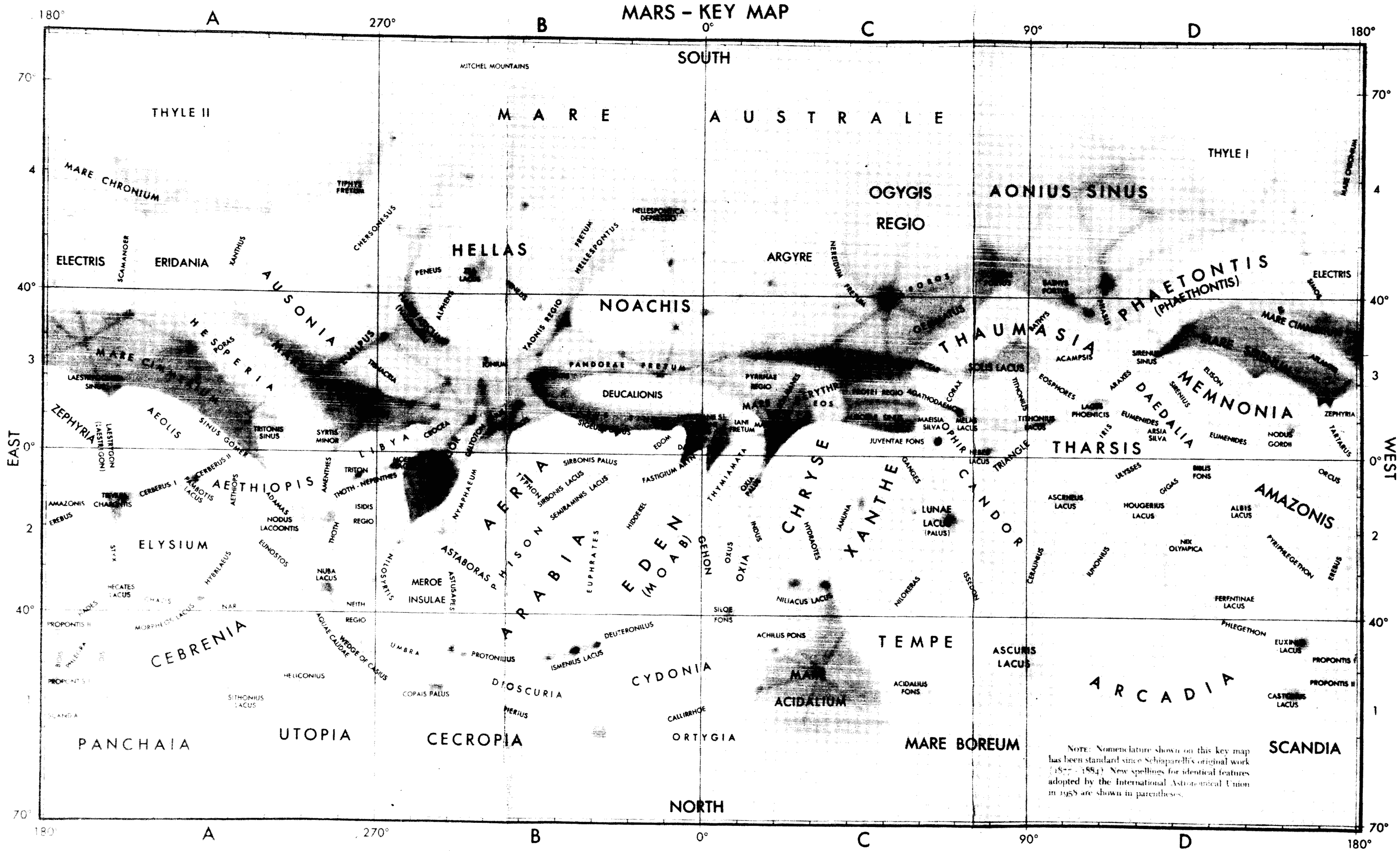
These photographs were taken at periods far from opposition and indicate that the blue clearing is not necessarily a function of opposition. Reproduced by permission of Lowell Observatory from MARS by E. C. Slipher.

PHOTO EVIDENCE OF LINES (CANALS) ON MARS.



Many photographs have been taken which indicate the existence of canals on Mars. Since photographs do not have the resolving power of the human eye, the drawings are possibly more representative of what is seen. Reproduced by permission of Lowell Observatory from MARS by E. C. Slipher.

Adamas	A2
Aethiopis	A2
Aethiops	A2
Agathodaemon	C3
Amenthes	A2
Aquae Calidae	A1
Argyre I	C4
Arsia Silva	D3
Astaboras	B2
Astusapes	B2
Atlantis	D3
Aurora Sinus	C3
Bathys	D3
Biblis Fons	D2
Casius	A1
Cimmerium	A3
Corax	C3
Daemone	C3
Dawes Bay	B3
Deucalion	B3
Deucalionis R	B3
Eden	B2
Elysium	A2
Eumenides	D3
Eunostos	A2
Euphrates	B2
Fastigium Aryn	B2
Ferentinae Lucus	D2
Gehon	C2
Hadriaticum	B3
Hellas	B4
Hellespontus	B4
Hesperia Strait	A3
Hydraotes	C2
Ionium	B3
Isidis-Libya	A2
Isidis Regio	A2
Jamuna Canal	C2
Lacus Phoenicis	D3
Laestrygon	A3
Laestrygonum Sinus	A3
Libya	A2
Libya-Syrtis	B2
Lucus Moeris	B2
Maeisia Silva	C3
Mare Acidalium	C1
Mare Australe	B4 C4
Mare Cimmerium	A3
Mare Erythraeum	C3
Mare Sirenum	D3
Mare Tyrrhenum	A3
Margaritifer Sinus	C3
Meridiani Sinus	B3
Mts. of Mitchel	B4
Nectar	C3
Nepenthes-Thoth	A2
Noachis	B3
Nodus Lacoontis	A2
Nuba Lacus	A2
Ophir	C3
Pandorae Fretum	B3
Phoenicis Lacus	D3
Poras	A3
Sabaeus Sinus	B3
Sinus Gomer	A3
Solis Lacus	C3
Syrtis Major	B2
Tharsis	D3
Thaumasia	C3
Thoth	A2
Thoth-Nepenthes	A2
Thoth-Nepenthes-Triton	A2
Tithonius	C3
Tithonius Lacus	C3
Ulysses	D2



30)Reproduced by permission of Lowell Observatory from MARS by E. C. Slipher.

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November 19, 1964

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THE MARTIAN ENVIRONMENT

By Robert B. Owen

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This document has also been reviewed and approved for technical accuracy.

Robert E. Smith

Robert E. Smith
Chief, Space Environment Group

W. W. Vaughan
Chief, Aero-Astrophysics Office

E. D. Geissler
Director, Aero-Astrodynamics Laboratory

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